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The monetary benefit of early flood warnings in Europe

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ABSTRACT

Effective disaster risk management relies on science-based solutions to close the gap between prevention and preparedness measures. The consultation on the United Nations post-2015 framework for disaster risk reduction highlights the need for cross-border early warning systems to strengthen the preparedness phases of disaster risk management, in order to save lives and property and reduce the overall impact of severe events. Continental and global scale flood forecasting systems provide vital early flood warning information to national and international civil protection authorities, who can use this information to make decisions on how to prepare for upcoming floods. Here the potential monetary benefits of early flood warnings are estimated based on the forecasts of the continental-scale European Flood Awareness System (EFAS) using existing flood damage cost information and calculations of potential avoided flood damages. The benefits are of the order of 400 Euro for every 1 Euro invested. A sensitivity analysis is performed in order to test the uncertainty in the method and develop an envelope of potential monetary benefits of EFAS warnings. The results provide clear evidence that there is likely a substantial monetary benefit in this cross-border continental-scale flood early warning system. This supports the wider drive to implement early warning systems at the continental or global scale to improve our resilience to natural hazards.

1. Introduction

Flood forecasting systems have become an essential part of flood risk management, across all spatial scales, from local to continental (Meyer et al., 2012; Pagano et al., 2014; Stephens and Cloke, 2014). Such systems require substantial investment for system development and considerable resources to run operationally (Cloke and Pappenberger, 2009; Thiemig et al., 2014). The European Flood Awareness System (EFAS) provides

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probabilistic flood forecasting information to national authorities within Europe, as well as to the Emergency Response Coordination Centre of the European Commission as early as 10 days before a flood event (Bartholmes et al., 2009; Thielen et al., 2009a). Development of the system began in 2003 with results disseminated to the users as 'research products'. EFAS has been fully operational since 2012, currently running 138 pan-European forecasts twice a day, every day, which requires extensive computer resources. EFAS forecasts and warnings are continuously improving (ECWMF, 2014; Haiden et al., 2014; Pappenberger et al., 2011), and the system has demonstrated valuable early warning capabilities in several recent events including the Balkan floods in 2014 (Thielen et al., 2014) and the Central European floods in 2013 (Haiden et al., 2014; Thielen, 2014).

Flood forecasts provide essential information for local and national authorities who must take decisions on actions (such as flood gate closures or evacuations) to protect citizens, property and infrastructure, particularly in urban areas and industrial zones. Flood forecasts are important for those authorities making decisions on the availability of disaster risk finance (Jongman et al., 2014a, 2014b). Floods also represent a threat to the environment and agriculture as was observed during the 2014 January floods in the UK (Stephens and Cloke, 2014).

In order for early flood warnings to be translated into decisions, clear mandates and responsibilities along the early warning chain from forecast to decision maker must exist. This is particularly important when assessing continental and global cross-border early warning systems, such as EFAS, as they can serve both as the main source of information in countries which do not have their own early warning system established, and also as an alternative source of information which can provide 'added value' where there is already national capability for monitoring and forecasting. In the latter case, civil protection actions are taken based on all the information available, and thus the benefit of this alternative information is not straightforward to determine. In addition, at the European level, the EFAS information is used directly for planning of aid and support before and after major flood events (EC, 2014a); again the monetary benefit is not straightforward to determine.

Merz et al. (2010) provide a review of flood damage assessment and highlight two key challenges, absence of data and uncertainty. Other studies, such as Sampson et al. (2014) highlight the large impact uncertain precipitation data have on flood damage calculations, in this case for insurance loss estimates. However, most studies in this area are usually set within the context of estimating economic damage based on flood risk in general (Carrera et al., 2015; Jongman et al., 2012; Meyer et al., 2013; Molinari et al., 2014; Pfurtscheller, 2014; Saint-Geours et al., 2014; Vilier et al., 2014). Such analysis is static in time and is only part of the picture for flood forecasting, which also requires consideration of flood response pathways and forecast performance.

Flood forecasting is one of the most effective flood risk management measures (UNISDR, 2004), and studies that have attempted to quantify avoided damages and forecast benefits include Parker (1991), Carsell et al. (2004), Priest et al. (2011), Molinari and Handmer (2011) and Verkade and Werner (2011). For example, Priest et al. (2011) analyse questionnaires sent after flood events at the national-level (England and Wales) and the local-level (Grimma, south-eastern Germany) to establish avoided costs of flood management with particular reference to flood forecasting. National and regional flood forecasts have been shown to provide benefit in the US (EASPE, 2002) and in Scotland (SNIFFER, 2006–2009), as have upgrades to hydro-meteorological early warning services in developing countries (Hallegatte, 2012). Case studies from individual flood events outside Europe have estimated flood forecasting system cost–benefit ratios of 1:500 for Bangladesh (Bangladesh 2007 floods, Teisberg and Weiher, 2008) and 1:176 for Thailand (Thailand 2007 floods, Subbiah et al., 2008). It is notable that in regions with a low frequency of floods such as Sri Lanka (2003 event) this ratio can drop substantially 1:0.93 (Subbiah et al., 2008). So in general the cost–benefit of flood forecasting systems compares extremely favourably to the cost–benefit of weather and climate services, which range from 1:2 to 1:20 (Frei, 2010; Perrels et al., 2013) or other early warning systems in general (Klafft and Meissen, 2011; Rogers and Tsirkunov, 2010).

Estimating the benefits of flood forecasting systems is limited not only by the underlying data (e.g. uncertainties of the vulnerability and exposure data, see Jongman et al., 2012) but also by many other uncertainties including the methods employed to estimate damages and avoided damages (Merz et al., 2010). The analysis presented in this paper uses avoided damages, and does not address the wider question of economic value. Estimating the economic value of a forecasting system as a whole is far more complicated (Benson and Clay, 2004; Bockstael et al., 2000; Merz et al., 2010; Parker, 2003) as it depends on:

- the starting point (e.g. what type of forecasting system already exists);
- the spatial and temporal dimensions (e.g. recent flood history; the lower economic value when compared with monetary value, associated with the European scale when compared with national or regional scales, when economic transfers are taken into account; and the higher value attained if a flood occurred just a few weeks ago);
- the scalability (response pathways cannot simply be multiplied across entire river regions as for example temporary defences are limited resources and be deployed everywhere).

In addition, in flood situations many decisions do not necessarily achieve the best possible outcome measured in monetary terms, as decisions can be made under duress (Choo, 2009) or influenced by other external limitations (e.g. availability of temporary flood barriers). Therefore, a flood forecasting system shares common properties with ecosystem services to humans, in that complex interactions lead to benefits which are often difficult to determine uniquely (Farber et al., 2006).

This study estimates the monetary benefits of a probabilistic continental scale flood early warning system, the European Flood Awareness System (EFAS). The study is based on EFAS early warnings and flood damage potential calculated from Barredo (2009), the EM-DAT (EM-DAT, 2014) emergency events database and complementary information from the

European Solidarity fund application (EC, 2014a). In the next section we describe the data and methods used to calculated avoided flood damages of EFAS early warnings, including details of EFAS flood forecasts, the EU and national forecasting context of EFAS, the flood alert decision rules, damage data sets and the calculation of potential avoided flood damages, and the sensitivity analysis used to provide an envelope of potential benefits to address the uncertainties and assumptions in directly assessing monetary benefit, and to identify the most important contributing factor. Results are presented and discussed in Section 3 in terms of flood occurrence and associated damages, the calculated potential benefits of EFAS early flood warnings and the sensitivity analysis. Conclusions are drawn in Section 4 as to the potential benefits of continental scale flood early warning systems.

2. Data and methods

In this section we describe the forecast data, the damage data and the methods used to calculate the potential avoided flood damages of the EFAS early warnings and the methods used to estimate the monetary benefit.

2.1. *The EFAS flood forecasts*

EFAS uses an ensemble of weather forecasts and a hydrological model to provide twice daily forecasts of river flow and flood warnings (e.g. Bartholmes et al., 2009; Pappenberger et al., 2005, 2011; Ramos et al., 2007, 2013; Thielen et al., 2009a, 2009b). Ensemble forecasts sample the uncertainty inherent in weather prediction and make many forecasts, known as ensemble members, by making alterations to the forecasting model or to the starting conditions (Buizza, 2003, 2015; Cloke and Pappenberger, 2009; Hagedorn et al., 2012; Vitart et al., 2008). EFAS uses numerical weather prediction data from the Deutscher Wetterdienst (German Weather Service, deterministic model COSMO-EU and global model), COSMO (high-resolution limited area model ensemble forecast with 16 ensemble members) and the European Centre for Medium-range Weather Forecasts (ECMWF, high resolution deterministic forecast and ensemble forecast with 51 ensemble members). The weather forecasts are used to drive the hydrological model which is set up on a 5×5 km^2 grid. At locations where real-time observations are available, the forecasts are bias corrected and post-processed (Bogner and Pappenberger, 2011; Bogner et al., 2012).

The EFAS forecasting system entered fully operational status in 2012 as part of the COPERNICUS Emergency Management Service (REGULATION (EU) No 377/2014). The estimated costs of the four EFAS operational centres, based on contracts awarded, is 21.8 M Euros. In addition, the development costs over 10 years are estimated to be on the order of 20 M Euros based on institutional and external support for EFAS (Thielen, pers. Commun.). The history of the EFAS development has 3 distinct phases: 2000–2007, where EFAS was in development, but national services already had access; 2007–2011, where EFAS was pre-operational; and 2012 onwards, where EFAS was fully operational. It is difficult to analyse these distinct phases as there is no information on how often EFAS forecasts were used in the first two phases, and so the analysis in this paper focuses on the last 'operational' phase; 2012–2013.

Performance of EFAS: Performance is evaluated against observed river flow and proxy observations (river discharge generated through running the model using observed meteorological variables) using a large range of probabilistic and deterministic scores. Performance is then assessed on both a continuous and an event basis, which includes a systematic analysis of EFAS warning 'hits' (both forecast and observation show a flood), 'false alarms' (forecast shows a flood but observation does not) and 'misses' (observations shows flood but forecast does not) since 2006. Pappenberger et al. (2011) showed that the system performance improves by 10–30% every decade. Performance is reported bi-monthly, in publicly available bulletins at www.efas.eu (Alfieri et al., 2014; ECWMF, 2014). It is also discussed annually with the EFAS stakeholders.

EFAS reforecast warnings: Each time the EFAS system undergoes a major update, a 'reforecast' is produced, where the new system is used to reproduce forecasts of past dates (this can be thought of as 'forecasts of the past' and is sometimes termed a 'hindcast' or a 'retrospective forecast'). The latest EFAS reforecast was in January 2014 following hydrological model improvements and new calibration (ECWMF, 2014; Salamon, 2014) and was used to evaluate the new changes to the system. This reforecast was computed for a continuous series of forecasts, with forecasts issued once a day looking 10 days ahead for every 5 km grid cell over the whole European area. The reforecast extends for 2 years from January 2012 to December 2013.

EFAS catchment-based flood warnings: The EFAS area is sub divided into 786 river catchments across Europe, which are used in the operational EFAS for monitoring and further post-processing. In this paper the reforecast is analysed to establish the hit, miss and false alarm rates for each catchment for the 2 year period 2012–2013 (catchment reforecasts). Also, for the reforecast data set the European average of the hit, miss and false alarm rates is also calculated (European average reforecasts).

2.2. *EFAS within the EU and national flood forecasting context*

Since inception, EFAS has established a partner network of more than 40 national and regional hydrological services. EFAS partners sign a *Conditions of Access* (CoA) agreement which defines the roles of EFAS and the receiving parties as well as the rules for communicating EFAS results. As per the CoA, EFAS real-time information and flood alerts are only distributed to established EFAS partners who can use the results for internal and external communications, planning and actions. Partners receive training on EFAS products and participate in the EFAS annual meetings where the latest developments and feedback on the system are presented (De Roo et al., 2011; Demeritt et al., 2013). Through these training and knowledge exchange mechanisms it is ensured that the national authorities have some ownership of the EFAS system and are in the position to be able to use the EFAS information in addition to their own warning systems. The advantage of EFAS is that national authorities can use the early-warning and probabilistic information to modify their own national warnings, particularly when these capabilities need supporting.

Furthermore, EFAS provides unique information for the European Civil Protection Mechanism to plan the deployment of aid ahead of a flood event, thereby reducing post-event response times. Here it is assumed that EFAS benefits are unique across Europe; this assumption is addressed in the sensitivity analysis and should be borne in mind when considering the results.

2.3. Decision rules for probabilistic flood forecasts

Probabilistic forecasting is more skilful than deterministic forecasting (Cloke and Pappenberger, 2009; Cloke et al., 2013; Pagano et al., 2014). Verkade and Werner (2011) have shown that probabilistic forecasts lead to higher benefits at all lead times in comparison to single valued forecasts. In deterministic forecasts the hit, miss and false alarm rates are fixed for a certain flood threshold, such as the 5 year return period level, or the 100 year return period level. An advantage of probabilistic forecasting is that the false alarm rates can be set to levels acceptable to the end user or stakeholders and therefore lead to better decisions that are tailored to specific circumstances (Cloke et al., 2013; Pagano et al., 2014; Ramos et al., 2010, 2013).

Probabilistic forecasting systems require sets of rules to convert forecasts into warnings (Dale et al., 2013), whereby the act of deciding to issue a warning is dichotomous – a warning is sent or not sent – and therefore deterministic. The optimal lead-time at which warnings are provided is therefore not always equivalent to the longest lead time available in the forecasts, as false alarms have to be balanced with successful warnings (for a discussion on this see Verkade and Werner, 2011). EFAS forecasters issue flood watches and alerts according to river catchment properties and forecast characteristics (Bartholmes et al., 2009) and also based on agreements with the national hydrological services.

A *flood alert* is issued when:

1. the catchment is part of the EFAS partner network (with signed agreements and training on the system);
2. the catchment area is larger than 4000 km^2;
3. the forecast is persistent, meaning that 3 consecutive ECMWF ensemble forecasts exceed the EFAS 5 year return period threshold with a probability of greater than 30%;
4. at least one deterministic forecast also exceeds this threshold;
5. the event is more than 48 h ahead with respect to the forecast date.

A *flood watch* may be issued by EFAS forecasters for EFAS partners when any of criteria 2–5 are not met, but the forecast situation warrants that the authorities should be informed. This leaves flexibility for interpretation and a flood watch can always be upgraded to a flood alert if the formal requirements are met.

A flood alert or watch is deactivated if:

1. Observations reported by the national/regional hydrological service clearly indicate that the EFAS Flood Alert/Watch is a false alarm.
2. Observations reported by the national/regional hydrological service clearly indicate that discharges/water levels have decreased to normal values although EFAS simulations still show that simulated discharge exceeds the EFAS high threshold.
3. The simulated EFAS discharge at the reporting point(s) for which the EFAS Alert/Watch was issued falls below the EFAS 5 year return period.

The above rules are used in this study with following modifications:

(i) Only 2 consecutive forecasts have been used to issue an alert, as the reforecast system only has 1 forecast per day (the operational system has 2 forecasts per day).
(ii) Only the last deactivation rule (number 3) has been used to deactivate flood alerts.
(iii) The reforecasts have been post-processed and combined at the outlet of each of the 786 catchments. The flood alert status is calculated only at these outlets under the assumption that this location is representative of the flood status of the upstream catchment.

The consequence of providing flood alerts only at catchment outlets, is that the number of flood alerts counted in the reforecasts will be less than for the operational EFAS, as under operational conditions a number of EFAS alerts are sent depending on the size of the flood event and the number of administrative authorities involved (several warnings for different rivers and authorities can be sent for one flood event).

2.4. Damage data sets

The collection of flood damage data is extremely challenging and it is therefore not possible to base this study on robust, detailed data (Merz et al., 2004, 2010). Such data are most often confidentially held by national authorities and are often only published externally for major flood events with a substantial time delay. Therefore, instead, three independent data sets and estimation methods have been used in order to accommodate some of the uncertainties involved in this exercise. All figures have been adjusted to 2012 prices (corresponding to when EFAS entered the operational phase) using the average inflation published by Eurostat, and in addition a 5% discount rate has been applied to discount future payoffs (European Commission, 2008). The damage data used in this study report flood events in a different way to both the operational EFAS and the reforecasts; floods are reported by country or by individual flood event (even if they spread across several catchments).

2.4.1. Barredo's flood damage map of Europe

The Joint Research Centre of the European Commission has produced a flood damage map of a 100 year return period (1% annual probability) for Europe assuming that all flood defences have been removed (Barredo, 2009). In this paper the EFAS catchment reforecasts 'hits' and 'misses' are combined with this flood damage map, with the original 100 m grid cells aggregated to river catchment scale. In order to calculate the benefit from issuing flood alerts it is necessary to estimate the annual average damages.

To calculate annual average damages, the Standard Weighted Annual Average Damage values (Penning-Rowsell et al., 2013, pp. 127–130) have been used to rescale the potential damage as identified by Barredo (2009). The annual avoided damages of different thresholds of standard protection, i.e. flood defences removed, flood defences at 20, 50 and 100 year flood return period protection levels, were also estimated (Penning-Rowsell et al., 2013, pp. 127–130). Fig. 1 shows the results of potential flood damage for catchments across Europe assuming no flood protection, i.e. all current protection is removed.

It should be noted that this approach has inherent uncertainties (Ward et al., 2011). The rescaling data are based on UK case studies and may not be entirely representative of pan-European conditions. In addition, the standardisation data are mainly based on older data and are likely to result in an overestimation of benefits. There is also some underestimation due to the use of the 100-year return period data as reference; the rescaling can only be applied where the 100 year values are above 0, and therefore some locations where there is no data for 100-year events, but less extreme events do occur, will be missed. It is not possible to exactly quantify these uncertainties.

2.4.2. *EM-DAT*

EM-DAT is an emergency events database which contains data and effects of many hazards (EM-DAT). From this database the number of flood events, and the monetary costs in USD, have been extracted for the European Continent. The costs have been adjusted using average inflation in Europe (Harmonized Index of Consumer Prices) to 2012 costs and converted into Euros (1 USD = 0.72 Euro). 2012 is used as the baseline year because this is the year in which EFAS became an operational system. EM-DAT contains no detailed information on return period, it is therefore assumed that any entry in EM-DAT would have warranted an EFAS flood alert. EM-DAT data also contain no detailed catchment information and cannot therefore exploit the detailed simulations provided by the reforecasts. Therefore the EM-DAT data is combined with the EFAS European average reforecasts for 2012–2013. It is possible to make two different extreme interpretations of the EM-DAT data depending on whether or not flood warnings are incorporated in the data. First, they can be seen as the damage resulting from having no warnings (termed "EM-DAT excl. warnings"). Second, they can be seen as the residual damages after warnings have been effective (termed "EM-DAT incl. warnings"). In practice, there is likely to be a mix of both of these on the European continent. For Europe, it can be assumed that most countries have short-term flood forecasting systems in place. It can further be assumed that with a growing EFAS partner network and the system becoming increasingly operational, early flood warnings have been taken into consideration.

2.4.3. *EU Solidarity Fund information*

The European Union Solidarity Fund (EUSF) was created in 2002 in response to the 2002 Elbe and Danube floods in Central Europe. It seeks to provide funds to help nations recover from natural disasters and express European solidarity with disaster-stricken regions. European nations can make requests to EUSF for support in relation to different catastrophic events including floods, forest fires, earthquakes,

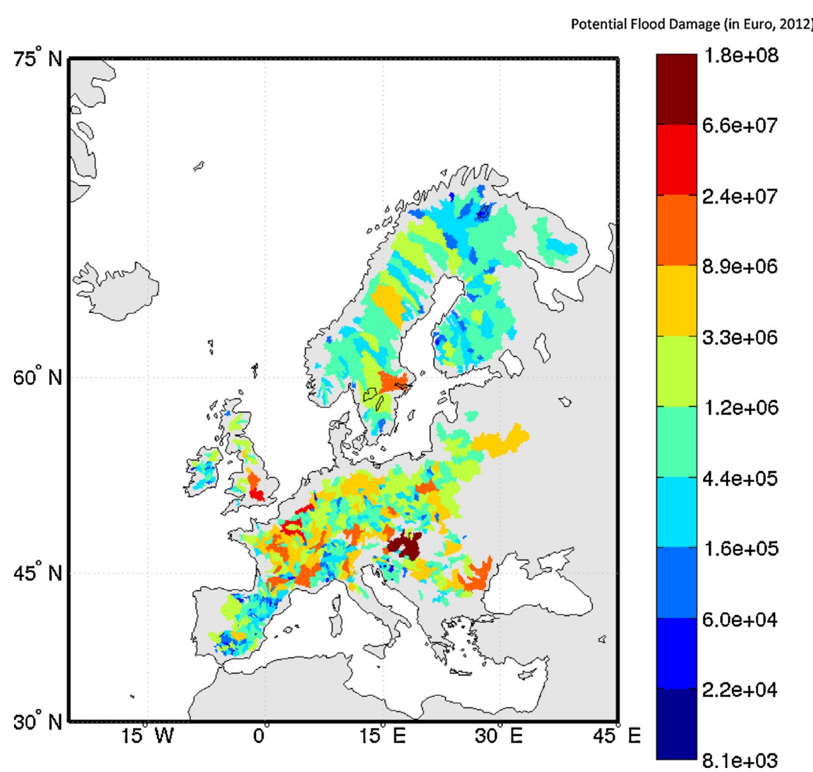

Fig. 1 – Potential flood damage (in Euro, 2012) aggregated on EFAS river catchments.

volcanic eruptions, storms and droughts. From 2002 to 2012 EUSF has provided funds to 15 countries recovering from flood events (36 out of 56 applications). The total reported flood damages amounted to 54 450 M Euro for which 5027 M Euros were paid as financial support to the applicant countries (Table 2). The highest damages were reported for the Elbe and Danube in 2002 (15 135 M Euros) and 2013 (10 309 M Euros). For the years 2007 and 2010 about half of the damages of 2013 were reported. Similarly to EM-DAT two interpretations regarding the damages can be made, and analysis must be based on European averages, so the EUSF data is combined with the EFAS European average reforecast for the period 2012–2013.

2.5. *Calculating potential avoided flood damages*

In this study, it is assumed that all EFAS warnings have been treated as operational messages by national authorities and at the EU level. Therefore, the response to warnings is assumed to lead, at least to some degree, to flood preparedness actions which is supported by evidence from the annual EFAS user workshop. Under this assumption, the avoided flood damages can be estimated. These are then compared with the system installation and running costs. The difference is considered to be the relative benefit of EFAS, and expressed in terms of the return on 1 Euro investment in the EFAS system.

Flood damage can be avoided through early warning leading to mitigation measures being taken by the warning recipients. The maximum potential flood damage (L_p) is related to the actual damage (L_a) by:

$$L_a(t) = n(t) * L_p$$

where $n(t)$ is the avoided damage reduction factor due to early warning.

There is a significant uncertainty in estimates of avoided flood damages, including different estimates from different sources and for different time horizons. The International Commission For The Protection Of the Rhine (2002) has estimated that flood warnings can help businesses avoid 50–75% of flood losses. Other estimates of potential avoided flood damages for flood warnings 48 h ahead, range from 4 to 40% (Carsell et al., 2004; Chatterton and Farrell, 1977; Day, 1970; Parker, 1991), although these figures also incorporate other factors such as coverage of flood warning service, service effectiveness and availability (Parker et al., 2005). Specifically considering domestic properties, SNIFFER (2006–2009) estimates that flood warnings result in avoided flood damages of 7.3%. However, even the estimates of this component of avoided damages have considerable uncertainty with other estimates of between 4.54 and 6% (Penning-Rowsell et al., 2013; Priest et al., 2011; Parker et al., 2007).

Table 1 lists the avoided damage factors for various pathways in responding to flood warnings (Parker et al., 2007, 2008; Scott and Wicks, 2012; Thurston et al., 2008). Although often employed together or in sequence, these pathways can be seen as different management options (Farber et al., 2006). All early warning pathways together result in a percentage avoided damage of 32.85% as the percentages always apply to the sum which was previously not saved. Using this figure for EFAS implies the assumption that the response to continental scale EFAS warnings is the same as the response to national and local flood warnings. Although necessary, this assumption does not take into account the difference in the context of the system, i.e. that EFAS warnings are used as an additional source of information by national flood warning authorities, and for response planning by European level civil protection.

There are several intangible and indirect costs or benefits of EFAS warnings that have not been considered in this study because of the difficulties in their estimation (for a classification of flood losses see Merz et al., 2010; Parker et al., 2005). It should be noted that for large scale disasters indirect losses may be of the same magnitude as direct losses (Hallegatte and Dumas, 2008). EFAS information is used in particular for evaluating aid scenarios, moving equipment to the right places if necessary, preparing transport routes or coordinating European aid. The costs of implementing such actions are low and hence assumed to be negligible in this study (similar to Hallegatte, 2012). The intangible benefits, such as the earlier provision of aid, which have been reported for example in the Central European floods of 2013 and the Balkan floods of 2014, are also not taken into account. Reputational damage can be significant (Subbiah et al., 2008) but is very challenging to cost accurately and hence has also been omitted from this study.

Table 1 – Avoided damages for various pathways in responding to flood warnings (adapted from Parker et al. (2008), Parker et al. (2007), Scott and Wicks (2012) and Thurston et al. (2008)). The percentages reflect avoided damages due to consecutive actions that can be employed.

Pathway	Description	Avoided damages due to early warning (%)
Flood Defence Operations (FDO)	Avoided damages by warning dependent flood defences	32%
Watercourse Capacity Maintenance (WCM)	Damages avoided by Water Course maintenance	0.9%
Community Based Operations (CBO)	Damages avoided by community-level defences	0.36%
Warning Dependent Resistance (WDR)	Residual damage avoided by warning-dependent (temporary resistance measures)	0.0036%
Contents Moved & Evacuated (CME)	Residual damages avoided by moving and evacuation property contents	5.7%
Early Warning measures	FDO, WCM, CBO	32.85%
Total	FDO, WCM, CBO, WDR, CME	36.68%

2.6. *Sensitivity analysis to generate an envelope of potential EFAS benefits*

Sensitivity analyses are recommended to assess the influence of uncertainties on model results (Cloke et al., 2008; Dobler and Pappenberger, 2013; Merz et al., 2008). Such an analysis, set within a cost–benefit analysis, can be used to prioritise development efforts and lead to a more efficient system improvement (Buganova et al., 2013). Here, a sensitivity analysis is undertaken to indicate the envelope of potential benefits of EFAS early flood warnings. The analysis tests 19 scenarios which take into account the main assumptions in the estimation of benefit: the avoided damage factors, the performance of the forecast system, the discount factors and the uncertainties in the damage data.

Avoided damage factors: The uncertainty in the avoided damage factors is discussed in Section 2.5. The values used in the sensitivity analysis are those presented in Table 1.

Forecast performance: Although issuing EFAS warnings is governed by underlying decision rules, in practice human judgement comes into play (Danhelka, 2015) and will impact upon the calculations of how good the forecast is (how much numerical skill the forecast has usually in comparison to a benchmark (Pappenberger et al., 2015)). As more data become available and the forecast system improves technically, the system skill would be expected to improve. Another assumption is that the forecast skill is stationary over a period of 20 years and this leads to an underestimation of the cost–benefit ratio. Earlier studies by Pappenberger et al. (2011) indicate that a performance improvement of 10% per decade is achievable. The sensitivity analysis tests warning performance improvements of 10%, 20% and 30%.

Discount factors: A discount factor represents the percentage rate used to calculate the present value of a future saving or income. It takes account of the lower value at present of future savings in comparison to present ones. In this study a discount factor of 5% across the EU has been employed (EC, 2014b). There are variations within Europe, with the UK using a factor of 3.5% and France using 4%. The sensitivity analysis tests the influence of using a lower discount factor of 3.5%.

Uncertainty of damage estimates: The uncertainties in the underlying damage datasets are also included in the sensitivity analysis. First the differences between using EUSF and EM-DAT are tested. It is not clear whether the Barredo (2009) data includes indirect damages; although Barredo (2009) reports that his analysis is based on direct costs, the EM-DAT documentation states that EM-DAT damage data includes indirect damages (although it is likely it only includes those indirect damages which are immediately apparent). 'Reported damages' at the time of the event often include elements of both direct and indirect damages because the disruptive effects of floods are apparent almost immediately (Merz et al., 2010). Uplift factors can be used to account for often unknown indirect damages, and are used as a multiplier on the direct costs. Such indirect costs include disruption to transport networks or mental health impacts or any factor which cannot be directly attributed to the floods but is indirectly related. Paccagnan (2012) suggests an average factor of 2.05 and a maximum and minimum of 2.54 and 1.75. We use these values to estimate our uncertainty bounds in our sensitivity analysis. In addition an extreme 'low boundary' scenario is used in the sensitivity analysis where the true damages are set at only 10% of EM-DAT excluding warnings.

3. Results

3.1. *Flood occurrence and associated damages*

The efficiency of a forecasting system can be defined as the number of hits divided by the total number of hits and misses. For the EFAS study, the efficiency (hit rate) amounts to 55% which is considerably less than the 70% which is seen as desirable for this type of system (Subbiah et al., 2008). However, the hit rate should not be used as a single performance measure (Armistead, 2013; Hogan and Mason, 2012).

In a perfect forecasting system the number of misses would be zero and the monetary savings would be the damage multiplied by 32.85% (see above), in which case over the period 2000–2013 on average every year 1092 M Euro or 1627 M Euro would be saved (using the EM-DAT data excluding and including warnings respectively). However, forecasting will also lead to misses and false alarms which will lead to a ineffectiveness in the warning chain in the case of misses and negative effects in the case of false alarms (Parker and Priest, 2012). Using the hit rate shown in Table 2 (on average 55% of all

Table 2 – Flood occurrence and associated damages for various data sources.

Data source	Descriptions	Years covered	Average
EM-DAT	Flood occurrence	2000–2013	18.2
	Damage (M Euros – 2012 prices)		3325
EUSF	Applications	2002–2013	2.8
	Damage (M Euros – 2012 prices)		4513
EFAS[a]	Alerts	2007–2013	23.4
	Hits		12.1
	False alarms		3.6
Reanalysis study	Alerts	2012–2013	14.2
	Hits		4.7
	Misses		3.8
	False alarms		9.5

[a] Note that EFAS transitioned into an operational service in 2012 and therefore no resources were available to follow up hits and false alarms in this year. Not all EFAS alerts have been verified to be hits or false alarms and their status is unknown.

hits and misses are hits), the average saving per year in the period 2000–2013 will be 607 M Euros or 858 M Euros (using the EM-DAT data excluding and including warnings respectively). The latter would rise to 782 M Euros or 1164 M Euros using the EUSF data excluding and including warnings respectively.

Table 2 shows the number of flood events recorded in EM-DAT (from 2000), reported flood damages in the EUSF applications from 2002 to 2013, as well as those reported by EFAS (from 2007; EFAS Dissemination Centre, 2014) and computed in this study (2012/2013). As expected from the discussion in Section 2.1, the number of EFAS alerts is greater than the number of events reported in the damage data sets. In addition, the number of events reported in the EM-DAT database is lower than the number of applications to the EUSF. This is because only events which exceed a certain threshold of a country's GDP qualify for the application and several events within a country may be regrouped into a single application. On average the EUSF damages from 2002 to 2013 are higher than the EM-DAT estimates. This indicates that (a) the majority of the costs arise from the major events that meet the criteria for EUSF applications and (b) the calculation of costs in EUSF is more comprehensive that the estimates in EM-DAT. Flood occurrence and damage data are not always correlated, for example the years 2012 and 2013 have the same number of floods but vastly different damages (not shown). This is because flood damage costs are related not only to flood occurrence but also to flood severity, duration and location. This illustrates the uncertainty in estimating flood-related costs.

3.2. *Benefit of EFAS*

Benefits of EFAS early warnings have been estimated using two different methods: (i) forecasts at catchment level have been used to calculate hits and misses which are then combined with Barredo's (2009) modified flood damage map for Europe; and (ii) the EM-DAT and EUSF damages for the period 2000–2013 have been used and combined with the average warning performance from an EFAS forecast study. These estimates have been modified using different standards of protection (for example, a 100 year flood return period standard of protection will be defences that protect against a flood level with a 1% annual probability of occurrence). A scaling between different protection standards can be found in Penning-Rowsell et al. (2013). Both analyses have been compared against the installation and running costs of the EFAS system, with the difference being the estimated net benefit of the EFAS system. Fig. 2 shows the net benefits of the current EFAS system and also a 'perfect' EFAS system (with no event misses). The figure shows the return on 1 Euro after 5 and 20 years, and the net benefits for no flood protection, 20, 50 and 100 year flood return period protections. The EM-DAT and EUSF results are also shown and are independent in terms of economic costs from the other data, but rely on the same model simulations.

Fig. 2 shows the results of the calculations of the benefits of the EFAS system. Assuming lower standards of protection the net benefits are higher. Fig. 2 shows that for a no protection scenario using the current system there would be a return of 1:495 Euro on EFAS investments after 5 years, which would increase to over 1:988 Euro after 20 years. In case of a perfect system the no protection scenario would give a return of 1:883 Euro after 5 years and 1:1760 after 20 years. The upper bounding threshold here is flood protection to the 100 year return period standard (which is unrealistic as average standards of flood protection across Europe are well below this level, see Jongman et al., 2014b). Even at this higher bound the benefit return decreases to only 1:7 after 5 years and to 1:13 after 20 years. The figure thus provides evidence that a net benefit of the EFAS system is very likely.

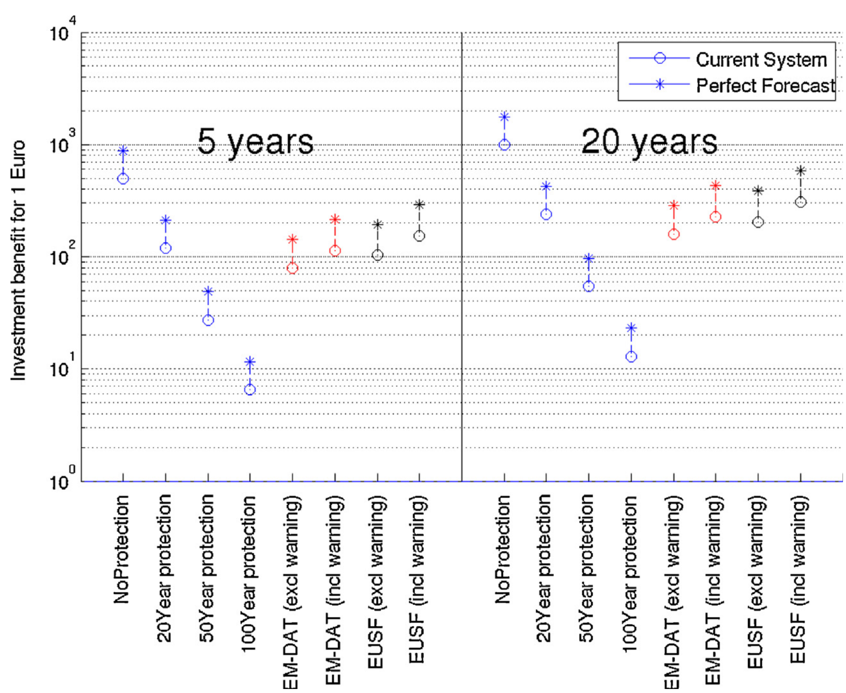

Fig. 2 – Net benefit of the European Flood Awareness System.

Table 3 – Sensitivity analysis of estimated cost-benefit ratio with percentage savings due to early warnings.

Pathway	Avoided damages due to early warning (%)	Ratio of monetary costs to benefits (after 20 years)	Scenario
Flood Defence Operations (FDO)	32%	1:155	1
Watercourse Capacity Maintenance (WCM)	0.9%	1:4	2
Community Based Operations (CBO)	0.36%	1:2	3
Warning Dependent Resistance (WDR)	0.0036%	1:0.02	4
Contents Moved & Evacuated (CME)	5.7%	1:28	5
Early Warning measures	32.85%	1:159	Base
Total	36.68%	1:178	6
Target Future	70%	1:339	7

The EM-DAT database facilitates independent assessment of this net benefit, as the data are independent in terms of economic costs from the other data (but rely on the same model simulations). The results for EM-DAT (excluding warnings) provide a return of 1:159. This is equivalent to returns of the 20 and 50 year return period values noted in the analysis above. The results for EM-DAT (including warnings) are equivalent to the 50 and 100 year return period results. The EM-DAT (excluding warnings) is used as a base scenario for the sensitivity analysis in the next section. Calculated as the net benefit considering the investment and the operating costs of EFAS this provides a return of 20 M Euros. The EUSF data provides further independent evidence that EFAS has net benefit. Here EUSF values (including warning) are equivalent to between 20 year protection and no protection.

3.3. *Sensitivity analysis*

The sensitivity analysis of the relative benefit of EFAS early flood warnings takes into account the main assumptions in the estimation of benefit, which includes the avoided damage factors, the performance of the forecast system, the impact of discount factors and the uncertainty of the damage estimates. The analysis is displayed in relation to the EM-DAT (excl. warnings) data although the sensitivity to other damage estimates is also shown.

As shown in Table 3 a base scenario is used as a reference for the sensitivity analysis. This scenario has avoided damages due to early warning of 32.85%, forecast performance equivalent to the current EFAS (55% efficiency), a discount rate of 5%, uses the EM-DAT data (excluding warning) and a monetary cost/benefit ratio, after 20 years of 1:159.

3.3.1. *Avoided damages factor*

In Table 3 the impact of a range of different avoided damages is shown, indicative of the wide range of responses to flood warnings. It can be seen that the system would not be worth the investment if only Warning Dependent Resistance measures were used (cost/benefit ratio of 1:0.02). All early warning measures together lead to a cost/benefit ratio of 1:159 (base scenario) whilst a fully inclusive warning chain would be 1:178 (scenario 6).

3.3.2. *Forecast performance*

Table 4 shows that with a base cost:benefit ratio of 1:159, a 10% improvement in forecast performance over 20 years would lead to an increase in the cost:benefit ratio to 1:173 (scenario 8), rising to 1:187 for 20% (scenario 9) and 1:200 for 30% (scenario 10). The estimated benefit–cost ratios of scenarios 8–10 are all less than the theoretical limit of 1:286 which could be achieved with a perfect warning system (scenario 11).

3.3.3. *Discount factors*

Table 4 illustrates the sensitivity towards these factors showing that a discount rate of 3.5% (scenario 12) leads to a ratio of benefits to costs of 1:176 (compared to 1:159 for the base scenario using 5%). This is the same level of sensitivity as to the 10% increase in skill.

3.3.4. *Damage estimation*

In Table 4 the difference that results from using the EUSF is apparent instead of the EM-DAT data, with EUSF data leading to a relative benefit of 1:205 (excluding warning – scenario 13) or 1:308 (including warning – scenario 14). EM-DAT in contrast

Table 4 – Sensitivity Analysis of estimated cost-benefit ratio with percentage savings due to early warnings set at 32.85% (excl stands for excluding warning and incl stands for including warning).

Warning performance	Current	10% better	20% better	30% better	Perfect	Current	Current	Current	Current	Current	Current	Current	Current
Discount rate	5%	5%	5%	5%	5%	3.5%	5%	5%	5%	5%	5%	5%	5%
Damage data	EM-DAT (excl)	EM-DAT (excl)	EM-DAT (excl)	EM-DAT (excl)	EM-DAT (excl)	EM-DAT (excl)	EUSF (excl)	EUSF (incl)	EM-DAT (incl)	175% EM-DAT (excl)	205% EM-DAT (excl)	254% EM-DAT (excl)	10% EM-DAT (excl)
Monetary cost/benefit ratio (after 20 years)	1:159	1:173	1:187	1:200	1:286	1:176	1:205	1:308	1:226	1:278	1:326	1:403	1:16
Scenario	Base	8	9	10	11	12	13	14	15	16	17	18	19

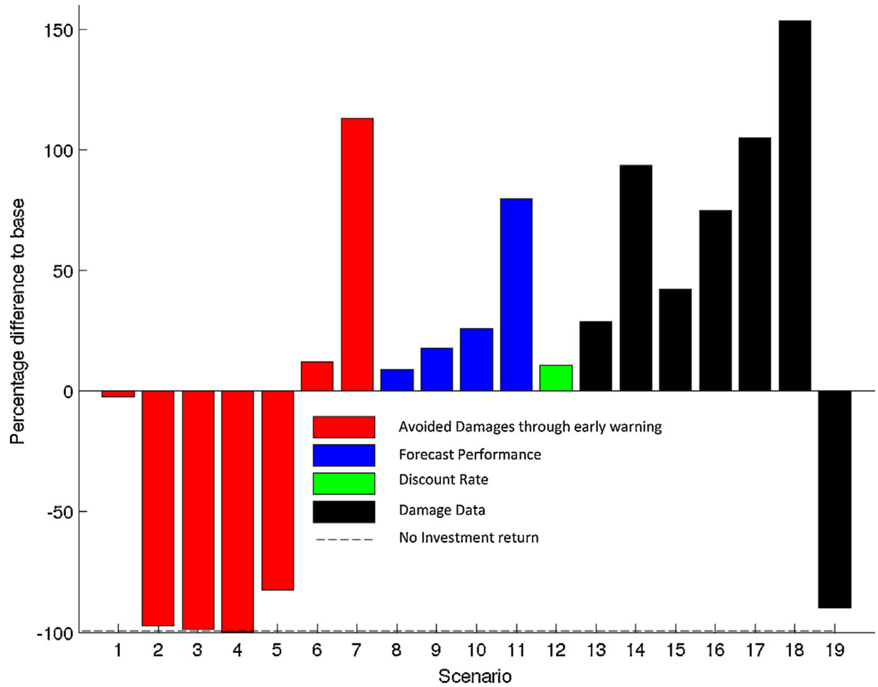

Fig. 3 – Sensitivity analysis of the relative monetary benefit of EFAS presented as the percentage difference of 19 scenarios as compared to the base scenario of all early warning measures (Tables 3 and 4).

leads to values of 1:159 (excluding warnings – base scenario) and 1:226 (including warnings – scenario 15).

The inclusion of uplift factors increases the benefit–cost ratio from our base case of 1:159, to ratios of between 1:278 (scenario 16) and 1:403 (scenario 18). In addition the 'low boundary' scenario (scenario 19), in which the true cost is only 10% of EM-DAT (excl warning), leads to a ratio of 1:16.

3.3.5. *Summary*

Fig. 3 summarises the results of the sensitivity analysis, with the bars showing the percentage difference of the results of the 19 scenarios to the base scenario results. The figure shows that there is a considerable range in the monetary benefit observed, with the avoided damages factor introducing the largest uncertainty. The estimation of the actual damage also introduces a large variation in the results followed by the potential system improvement in the future. The lowest impact on the results is given by the discount rate. This is summarised in Fig. 3 where the sensitivity analysis of the relative monetary benefit of EFAS is presented as the percentage difference of the scenarios as compared to the base scenario of all early warning measures (Tables 3 and 4). In only one case (scenario 4) is there a relative cost, and the envelope of values indicates confidence in the relative monetary benefits of EFAS.

4. Conclusions

In this paper, the benefits of a continental scale early flood warning system, the European Flood Awareness System (EFAS), were analysed in monetary terms. Three different monetary data sets on flood damages were combined with flood forecasts to provide evidence that there is substantial net benefit provided by this pan-European system. This supports the wider drive to implement early warning systems at the continental or global scale to improve our resilience to natural hazards in a changing climate (Alfieri et al., 2013; De Groeve et al., 2014; Merz et al., 2014; Pappenberger et al., 2012, 2013; Ward et al., 2013, 2014; Winsemius et al., 2013).

The uncertainty in the estimates of potential avoided flood damages was tested with a detailed sensitivity analysis of the avoided damages factor, the forecast performance, the impact of discount factors and the uncertainty of the damage datasets. The envelope of estimates of benefit provided robust evidence of system benefit. The base scenario in this analysis, considered to be conservative, demonstrates that for every Euro invested a return of 159 Euros is created after 20 years of operating EFAS (return of 20 trillion Euros). This value compares extremely favourably to the cost benefit of weather and climate services which range from 1:2 to 1:20 (Perrels et al., 2013) or other early warning systems in general (Klafft and Meissen, 2011).

Varying the avoided damages factor due to early warning has a large impact on the results and for example if the pathway of action due to an early warning comprises only water course maintenance, then the cost benefit ratio would reduce to 1:4. In contrast, improved forecast performance could lead to an increase of the cost benefit ratio to 1:202. Ratios of up to 1:409 were possible.

The sensitivity analysis highlights that the largest uncertainty in these estimates comes from the avoided damages through early warning percentages which reflect the wide range of possible responses to flood warnings. Another large source of uncertainty is the damage data used in the derivation of the monetary benefit. This highlights the importance of forecast responses in making the most out of a flood forecasting system. This could also be actively improved and would result in a greater overall benefit, although it may have a high cost. Although not as great as the damage data and the avoided damage percentages, there is still scope to improve the system benefit by improving forecasting system performance. One clear conclusion of this study is that investment in medium range probabilistic flood forecasting systems is always valuable assuming multiple pathways of actions are taken, because the cost benefit ratios are always positive. This suggests that these flood forecasting systems should be high priority for long term investment and support, because they are effective and save money as well as lives.

As well as providing evidence of the benefits in continental scale early flood warning systems, the study has also shown that improving our resilience to floods and realising the full benefits of such early warning systems requires a focus on more than just improving forecast skill. The response to warnings, including visualisation, better training and response procedures are extremely important in making the most of these early warnings and should be priorities for future investment. The example of EFAS also demonstrates the value of regional cooperation, knowledge exchange and interdisciplinary research teams in developing continental scale early warning systems. Early warning systems, however valuable, are only one part of our flood management portfolio, and should be employed alongside other measures to make our populations more resilient to flood events, for example by considering urban design features and green infrastructure to mitigate floods and reduce flood damage. In conclusion, this study has provided evidence that a continental scale early flood warning system can provide valuable information that prevents substantial flood damage and aids disaster recovery. This evidence can be used to support development in other continents to improve resilience, particularly in vulnerable areas, where early warning systems could provide the difference between stability and economic collapse.

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